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Binaural-Bimodal Fitting or Bilateral Implantation for Managing Severe to Profound Deafness: A Review

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There are now many recipients of unilateral cochlear implants who have usable residual hearing in the non-implanted ear. To avoid auditory deprivation and to provide binaural hearing, a hearing aid or a second cochlear implant can be fitted to that ear. This article addresses the question of whether better binaural hearing can be achieved with binaural/bimodal fitting (combining a cochlear implant and a hearing aid in opposite ears) or bilateral implantation. In the first part of this article, the rationale for providing binaural hearing is examined. In the second part, the literature on the relative efficacy of binaural/bimodal fitting and bilateral implantation is reviewed. Most studies on comparing either mode of bilateral stimulation with unilateral implantation reported some binaural benefits in some test conditions on average but revealed that some individuals benefited, whereas others did not. There were no controlled comparisons between binaural/bimodal fitting and bilateral implantation and no evidence to support the efficacy of one mode over the other. In the third part of the article, a crossover trial of two adults who had binaural/bimodal fitting and who subsequently received a second implant is reported. The findings at 6 and 12 months after they received their second implant indicated that binaural function developed over time, and the extent of benefit depended on which abilities were assessed for the individual. In the fourth and final parts of the article, clinical issues relating to candidacy for binaural/ bimodal fitting and strategies for bimodal fitting are discussed with implications for future research.

Keywords: bimodal hearing; bilateral implantation; deafness

Introduction

The provision of binaural hearing to people who have bilateral hearing impairment is important because binaural hearing provides better speech perception and sound localization over monaural hearing.[1-5] Furthermore, auditory stimulation to both ears prevents neural degeneration that is associated with auditory deprivation.[6-11] For people who have profound deafness in both ears, binaural hearing can be provided only with bilateral implantation. For people who receive a cochlear implant in one ear and who have residual hearing in the nonimplanted ear, binaural hearing can be achieved by either bilateral implantation or by the use of a cochlear implant with a hearing aid in opposite ears (binaural/bimodal stimulation). This article addresses the question of whether binaural/bimodal stimulation or bilateral implantation offers greater advantages to recipients of unilateral cochlear implants who have residual hearing in the opposite ear.

This article is divided into 5 parts. In the first part, the rationale for providing binaural hearing is outlined, and the extent to which bimodal stimulation and bilateral implantation would be expected to provide binaural benefits is examined. In the second part, the literature on the relative effectiveness of bimodal stimulation and bilateral cochlear implantation is reviewed. Because of methodological limitations in the studies, there is insufficient evidence to determine whether bimodal stimulation or bilateral implantation is more effective. For this reason, we carried out a

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crossover comparison of adults who switched from bimodal stimulation to bilateral implantation. The pilot results from two adults are reported in the third part of the article. In the fourth and final parts of the article, clinical issues on candidacy for bimodal fitting and strategies for fitting are discussed together with implications for future research.

Rationale for Providing Binaural Hearing

Hearing sounds in both ears makes it possible to locate the source of sounds. Because of the size of the head and the position of the ears, the intensity and arrival time of sounds at the two ears differ according to the location of the sound source relative to the ears. The head acts as an acoustic barrier, producing a boost of sounds on the near side of the head and an attenuation of sounds on the far side of the head. This "head diffraction" becomes less effective when the wavelength is less than the diameter of the head. Therefore, interaural level differences are more pronounced for sounds with frequencies above 1500 Hz than those below it.

The arrival time of sounds at the two ears depends on the location of the sound source relative to the listener, the speed of sound, and the size of the head. Whereas no appreciable difference between ears occurs for sounds from straight ahead, more displacement of the sound source to one side results in greater differences in arrival time at the two ears. Any time delay leads to a phase delay; hence, an interaural time difference results in an interaural phase difference. As neural responses are highly synchronized to the sound waveform only for low-frequency sounds, interaural time difference cues are most efficiently carried in the low frequencies up to about 1500 Hz.[12]

Localization

A person who receives auditory stimulation in only one ear may be able to tell whether a sound comes from the right or left side (side discrimination) by knowing that the louder sounds are more likely to come from the aided/implanted side. To perceive the location and direction of sounds, however, it is necessary to make use of interaural time and level differences.[13] For this reason, the provision of binaural/bimodal stimulation or bilateral implantation would almost certainly lead to better localization ability than unilateral stimulation.

Several factors affect access to interaural time and level difference cues. First, the availability of accurate interaural time difference information depends on the fidelity of devices in preserving timing information. Time delays measured in hearing aids are generally less than 5 milliseconds,[14] and timing information is well preserved with hearing aids. As shown by Byrne and Noble,[15] users of bilateral hearing aids are able to make effective use of interaural time difference cues carried in the amplified low frequencies for locating the source of sounds. On the other hand, cochlear implants do not preserve fine-timing information.[16] In current implant systems, all processing strategies, except the analog-based strategies, extract only the temporal envelope of incoming signals from up to 22 frequency bands and amplitude-modulate it to a fixed-rate pulsatile carrier. They do not convey the fine temporal structure of sounds that forms an important basis for detecting interaural time differences.[17] Although the temporal envelope could potentially convey timing information, interaural time differences would be inconsistent because of the variations in interaural time difference detection thresholds across electrodes[18] and the lack of synchronized stimulation in bilateral cochlear implants. Low-frequency information is represented neither by the place of stimulation[19] nor by the temporal fine structure of the firing pattern. Therefore, it is likely that combining low-frequency fine-timing information via a hearing aid with high-frequency information via a cochlear implant in opposite ears would be more effective in conveying interaural time difference cues than combining two cochlear implants.

Second, the processing times of bilateral devices are likely to result in offsets that affect interpretation of interaural time difference information. If these offsets are small and constant, listeners could potentially adapt their localization to these cues.[20,21] Otherwise, the information between ears might be too distorted to be useful to the listeners. The risk of inadequate representation of timing information between ears is likely to be greater in bilateral stimulation that involves combining a hearing aid and a cochlear implant than that involving two cochlear implants.

Third, access to interaural level difference cues relies on adequate preservation of the physical differences in level between ears. In bilateral stimulation which involves two separate signal processors with independent gain control circuitry, interaural cues may be decreased or distorted unless gains or loudness percepts are balanced between ears. For instance, Tyler et al[22] demonstrated how a user of bilateral implants who displayed localization offset to the left side could be corrected by increasing the gain on the right implant. In the same user, localization offset to the right could be achieved by further increasing the gain to the right implant. The same would possibly occur with bimodal stimulation when a hearing aid and a cochlear implant were not adjusted to give loudness balance between ears. Compression characteristics that are not matched across bilateral devices would also be expected to affect the use of interaural level difference cues for localization of sounds presented at different input levels.

Speech Perception

Head diffraction, binaural redundancy, and binaural squelch. Listening with two ears is better than one in understanding speech in a noisy environment.[23,24] The binaural benefit is thought to arise from a combination of head diffraction, binaural redundancy, and binaural squelch effects (see Dillon[25] for a summary). Head diffraction generates interaural differences in level for different source locations, thereby causing the signal-to-noise ratio (SNR) to be greatly different at one ear than at the other. With binaural hearing, listeners would be able to attend selectively to the ear with a better SNR. On average, the advantage because of head diffraction is about 3 dB.[26] Even if the SNR at the two ears is the same, the binaural auditory system can combine inputs from both ears to partially reduce the impact of noise on understanding speech. Binaural release of masking can improve speech intelligibility by up to 12 dB when speech and noise come from different directions.[27,28] On average, this "binaural squelch" effect gives an advantage of about 2 dB.[23,29] When speech and noise come from the same direction, being able to listen to the same sounds "twice" by listening with both ears gives an advantage because of "binaural redundancy" of about 1 to 2 dB improvement in SNR.[29,30]

The advantages arising from these effects should apply to both bimodal stimulation and bilateral implantation as long as sounds are audible in both ears. It may be expected that interaural time difference cues are much reduced and distorted for users of bilateral implants because electrical stimulation does not convey adequate temporal information,[31,32] and processors that are not synchronized for stimulation timing between the two ears would give rise to offsets that are well in excess of any natural head-induced delays.[33] Nonetheless, the effects of head diffraction and binaural redundancy should benefit users of bimodal stimulation and bilateral implantation alike.

Complementarity. For bimodal hearing, there is an additional potential advantage that arises from combining low-frequency information delivered via a hearing aid with high-frequency information delivered via a cochlear implant. Because the two types of information complement each other, we will refer to this advantage as "complementarity."

The low frequencies of speech contain information about the voice fundamental frequencies of the talker. Speech recognition in the presence of a competing talker can be enhanced by segregating the components on the basis of voice pitch cues,[34-36] even at poor SNRs.[37] Voice pitch information also contributes to linguistically significant distinctions. On the segmental level, voice onset time helps to distinguish between voiced and voiceless sounds.[38] On the suprasegmental level, variations in voice pitch convey lexical information in tone languages[39,40] as well as information relating to stress and intonational patterns in tonal and nontonal languages.[41] Conversely, the high frequencies of speech contain important linguistic information that relates to manner and place of articulation of consonants.[38]

Acoustic amplification in the low frequencies where residual hearing is usually best can provide voice pitch information that assists with segregation of competing voices and with making voicing and tonal distinctions by users of cochlear implants. Even when speech perception by the use of hearing aid alone is not possible,[42,43] the low-frequency pitch information provided by acoustic hearing complements the midfrequency and high-frequency information provided by electric hearing to enhance speech intelligibility.

Sound Quality and Music Perception

Sound quality relates to the perceived effects of variations in the frequency spectrum and the amplitude envelopes over time.[44,45] Subjective judgments of the quality and pleasantness of sounds and recognition of melodies by implant users are generally poor.[46-49] This is possibly because limited pitch and spectral details of sounds are delivered to the users. In most implant sound processors, the short-term spectral shapes of acoustic signals are estimated using a bank of bandpass filters (eg, 22 frequency bands are available to span the range from about 100 to 10 000 Hz in the Nucleus system). The number of bands that can be used to present electric stimuli to the cochlea is constrained by the number of filter bands, the number of electrodes implanted, and the number of active channels in the cochlear implant MAP. Because the acoustic features of complex sounds are much more degraded in electrical than in acoustic stimulation, combining acoustic hearing with electric hearing would be expected to improve sound quality and enhance music perception for users of cochlear implants in general.[50]

Evidence on Effects of Bilateral Stimulation

In this section, the relative effectiveness of binaural/bimodal fitting or bilateral implantation is first compared separately to monaural hearing via a unilateral cochlear implant for children and adults. A literature search of PubMed was conducted to identify published articles that have studied the use of cochlear implants by children and adults. Specific keywords that were used included "cochlear implants," "hearing aids," "bilateral implantation," "bimodal hearing," "electrical stimulation," "acoustic hearing," and "binaural hearing." The abstracts were reviewed to include only studies that reported the use of binaural hearing provided by either combining a cochlear implant and a hearing aid or by the use of bilateral cochlear implants. Where articles on bimodal hearing devices were concerned, only those that reported subjects with measurable hearing thresholds were included. Studies on users of bilateral cochlear implants that compared binaural to monaural performance were reviewed. The present discussion focuses on whether a second implant or a hearing aid would benefit recipients of unilateral cochlear implants who have usable residual hearing in the nonimplanted ear.

The methods and results for studies on localization and speech perception are shown separately in Tables 1 and 2. As will be seen, the sample size in all studies is generally small, and the variability in binaural effects among subjects is large. Hence, this review examines the number of individuals that showed significant binaural advantages, the number that performed similarly in monaural and binaural conditions, and the number that showed degradation in performance when switched from monaural to binaural hearing in different test conditions in each study.

Localization

The present literature search produced 10 studies that compared performance in localization with unilateral cochlear implants to that with bilateral cochlear implants and 8 studies that compared performance with unilateral cochlear implants to that with binaural/bimodal hearing devices (see Table 1). Localization benefit is defined as lower root mean square (rms) error with binaural hearing (using bimodal hearing devices or bilateral implants) than with monaural hearing (using a unilateral cochlear implant).

Bimodal stimulation. Across all studies on bimodal stimulation for adults, about half of the subjects showed significant binaural advantages for localization, and the remaining subjects performed equally poorly with binaural and monaural hearing. For children, about 62% showed improvement, while the remaining showed equivalent performance between binaural and monaural conditions. In most studies, the users of bimodal hearing devices have limited residual hearing in the nonimplanted ear (pure tone average [PTA] at 0.5, 1, and 2 kHz was 90 dB hearing level [HL] or greater). No systematic relationship was found between their PTA and extent of binaural benefits[62] (see Ching[89] for a summary) possibly because the analyses lacked power as a result of the restricted range of hearing threshold levels. Where performance with hearing aid alone was reported, it was not predictive of binaural benefits.[42] Nevertheless, it would reasonably be expected that more information would be received via acoustic amplification if the users of bimodal hearing devices had better residual hearing. Seeber et al,[52] for instance, described an individual with a PTA of 66 dB in the nonimplanted ear who localized nearly as well as normal-hearing subjects.

There is some evidence to indicate that when children's hearing aids were adjusted to amplify sounds to match the loudness of their contralateral cochlear implants, they localized sounds better than when the hearing aids were not adjusted with the cochlear implants.[59] Furthermore, a study on the effect of auditory experience indicates that children who had not used a hearing aid in the nonimplanted ear for up to 7 years demonstrated some binaural benefits in localization at about 8 weeks after a hearing aid was fitted to the nonimplanted ear and fine-tuned with the contralateral cochlear implant.[60]

Bilateral implantation. Across studies on bilateral implantation, 89% of adults showed binaural advantages,

Table 1. Summary of Studies on Localization

Study	Subjects	Method/Outcomes Measure	Results	Comments
Adults: bimodal				
1. Tyler et al (2002)[51]	CI-22 (n = 1), Clarion (n = 2) Total n = 3 Age = 53-64 years	Discriminate whether speech noise bursts at 73 to 83 dB SPL come from left or right 2 loudspeakers, ±45° Compare binaural errors with monaural errors	+2 =1	
2. Ching et al (2004)[42]	Nucleus CI-24 n = 18 Age = 25-84 years	Identify source of pink noise bursts at 70 dB SPL 11-loudspeaker array," −90° to 90° Compare binaural errors with monaural errors	+12 =6	Hearing aids were optimized with cochlear implants; balanced loudness between ears
3. Seeber et al (2004)[52]	Combi 40+ (n = 10), CI-24M (n = 1) Total n = 11 Age = 29-79 years	Identify source of broadband noise at 70 dB SPL 11-loudspeaker array, −50° to 50° Compare binaural errors with monaural errors	+5 =11	2 showed localization ability; the remaining showed side discrimination ability
4. Dunn et al (2005)[53]	CI-24 (n = 6), Clarion (n = 6), Total n = 12 Age = 48-76 years	Identify source of everyday sounds at 60 dBA 8-loudspeaker array, −45° to 45°	Only binaural rms errors were obtained	Adjusted volume of CI to match loudness of clinician's voice in the HA
Adults: bilateral CI				
5. Gantz et al (2002)[54]	Nucleus CI-24M n = 10 Age = 35-75 years	Discriminate whether speech noise bursts at 73 to 83 dB SPL come from left or right 2 loudspeakers, ±45°	+10	4 subjects had some left-right discrimination ability monaurally
6. Tyler et al (2002)[55]	Simultaneous, CI-24M n = 7 Age = 35-71 years	Discriminate whether speech noise bursts at 73 to 83 dB SPL come from left or right 2 loudspeakers, ±45°	+6 =1	Results at 3 months after activation of cochlear implants
7. Van Hoesel et al (2002)[33]	Case report CI-24M, sequential n = 1 Age = 51 years	Identify source of broadband noise at 70 dB SPL 11-loudspeaker array, −90° to 90°	+1	
8. Van Hoesel and Tyler (2003)[56]	Simultaneous, Nucleus CI-24M n = 5 Age = 36-71 years	Identify source of pink noise bursts at 65 dB SPL 8-loudspeaker array spanning 108°	+5	
9. Nopp et al (2004)[57]	Sequential (n = 17), simultaneous (n = 3) MED-EL Combi 40/40+ Total n = 20 Age = 17-67 years	Identify source of speech-shaped noise bursts at 60, 70, or 80 dB SPL 9-loudspeaker array, −90° to 90°	+18 −2	The 2 subjects who showed poorer binaural than monaural performance were deafened at early childhood

(continued)

Table 1. (continued)

Study	Subjects	Method/Outcomes Measure	Results	Comments
10. Seeber et al (2004)[52]	Sequential n = 3 Age = 20-65 years	Identify source of broadband noise at 70 dB SPL 11-loudspeaker array, −50° to 50°	+2 =1	1 showed accuracy close to normal; 1 showed side discrimination; the other showed limited ability
11. Litovsky et al (2004)[58]	Simultaneous, Nucleus CI-24R n = 17 Age = 52.7 years	Identify source of pink noise bursts at 65 dB SPL using a two-alternative forced choice task 8-loudspeaker array, −70° to 70°	+4 =2 Other individuals not reported	
12. Senn et al (2005)[31]	Sequential, MED-EL Combi 40+ n = 3 Age = 50-53 years	Minimum audible angle assessed at 8 reference positions (every 45°) using a two-alternative forced choice task	+3	
Children: bimodal				
2. Ching et al (2001)[59]	Nucleus CI-22M, CI-24M n = 11 Age = 6-18 years	Identify source of pink noise pulses at 65 dB SPL 11-loudspeaker array, −90° to 90°	+7 =4	Hearing aids adjusted to complement cochlear implants
13. Ching et al (2005)[60]	Experienced CI + HA users (n = 8), new users (n = 10) Total n = 18 Age = 6-18 years	Identify source of pink noise pulses at 70 dB SPL 5-loudspeaker array, 30° apart	+12 =6	CI + HA experience was not significantly correlated with binaural benefit
14. Litovsky et al (2006)[61]	Nucleus CI-22 or CI-24 (n = 4), Clarion (n = 1), MED-EL C40+ (n = 1) Total n = 6 Age = 4-14 years	Minimum audible angle, using a two-alternative forced choice task Spondaic words presented at 60 dB SPL Identify whether words originate from left or right 15-loudspeaker array, −70° to 70°	+4 =1	
15. Litovsky et al (2006)[62]	Nucleus CI-22 or CI-24 (n = 6), MED-EL C40+ (n = 2) Total n = 8 Age = 6-14 years	Minimum audible angle, using a two-alternative forced choice task Spondaic words presented at 60 dB SPL Identify whether words originate from left or right 15-loudspeaker array, −70° to 70°	+4 =3 −1	A few children performed as well as children with bilateral implants; all reported benefit with HA CI + HA benefit not related to hearing thresholds
Children: bilateral CI				
16. Litovsky et al (2004)[63]	Nucleus CI-22 (n = 1), CI-24 (n = 2), sequential Total n = 3 Age = 8-12 years	Identify source of pink noise pulses at 60(±4) dB SPL, using a two-alternative forced choice task 15-loudspeaker array, −70° to 70°	=3	Measurements at 3-month and 9-month intervals after bilateral implantation were similarly poor

12. Senn et al (2005)[31]	Sequential, MED-EL Combi 40+ n = 2 Age = 14 years	Minimum audible angle assessed at 8 reference positions (every 45°), using a two-alternative forced choice task	+2	Measured at 2 years postimplantation
14. Litovsky et al (2006)[61]	Nucleus CI-22 or CI-24, Clarion n = 13 Age = 3-16 years	Minimum audible angle, using a two-alternative forced choice task Spondaic words presented at 60 dB SPL Identify whether words originate from left or right 15-loudspeaker array, −70° to 70°	+5 =4	4 children could not do the task Children with more than 13 months' bilateral experience performed better
15. Litovsky et al (2006)[62]	Nucleus CI-22 or CI-24, Clarion n = 6 Age = 3-14	Minimum audible angle, using a two-alternative forced choice task Spondaic words presented at 60 dB SPL Identify whether words originate from left or right 15 loudspeaker array, −70° to 70°	+6	Improvement ranged from 11° to 72°

Note: In the "Subjects" column, "simultaneous" refers to users who received bilateral implants during the same operation, whereas "sequential" refers to users who received two implants in two operations with a time lag between the first and the second device. In the "Results" column, the number of subjects who obtained significant binaural benefits is indicated by "+," who performed similarly across monaural and binaural conditions is indicated by "=," and who performed poorer binaurally than monaurally is indicated by "–."

4% showed poorer binaural than monaural performance in localization, and the remaining subjects performed equally with both conditions. For children, 65% showed better binaural than monaural performance, with the remaining children showing similar performance between conditions when they used a unilateral implant and when they used bilateral implants.

For some adults who were postlingually deafened, binaural benefits for localization were evident at 3 months after bilateral implantation.[55] Nevertheless, several studies reported that some bilateral implant users did not show any difference in localization between monaural and binaural conditions[52,55,58] (see Table 1). Some users showed side discrimination ability but were unable to identify the source of sounds from an array of loudspeakers.[52] Furthermore, Nopp et al[57] reported that two users of bilateral implants who were deafened at early childhood demonstrated poorer binaural than monaural performance. In children, learning effects beyond 1 year after implantation, both in monaural and binaural conditions, are indicated.[61] Some children who had more than 13 months of bilateral experience demonstrated localization benefits with bilateral implants, whereas other children with similar experience displayed no improvement.[61,63] It is worth noting that some adults and children demonstrated the ability to tell whether sounds came from the left or the right by the use of unilateral cochlear implants.[54] Presumably, sounds that were louder and had more high-frequency emphasis would be identified as sounds from the implanted side. This implies that test methods requiring only left-right discrimination might not provide an adequate measure of binaural hearing ability.

Summary and discussion. Current evidence on bimodal stimulation and bilateral implantation indicates that

Table 2. Summary of Studies on Speech Perception

Study	Subjects	Method/Outcomes Measure	Results	Comments
Adults: bimodal fitting				
1. Shallop et al (1992)[64]	n = 7	Sentence, word, vowel, and consonant scores in quiet	+5 =2	Tested at 6 and 12 months postimplantation
2. Dooley et al (1993)[65]	n = 4 PTA = 96-116 dB HL	Words and sentence scores, vowel and consonant scores in quiet	=4	Ceiling effects for vowels, words, sentences Bimodal processor not superior to own hearing aid with cochlear implant
3. Armstrong et al (1997)[66]	Nucleus CI-22 n = 12 3FA = 75-112 dB HL	Sentence and word scores	Significant binaural advantage on average	No individual data reported
4. Syms and Wickesberg (2002)[67]	n = 6	Word and sentence scores in quiet and in noise	+5 =1	Ceiling effects for words in quiet
5. Tyler et al (2002)[51]	Nucleus CI-22 (n = 1), Clarion (n = 2) Total n = 3	Monosyllabic word and sentence scores in quiet and in babble Speech from the front, noise from the front or from 90° to the right or left	Quiet: =3 Noise: +2 =1 Binaural advantage with noise on implant side: +1 =2 Noise on hearing aid side: =3	
6. Luntz et al (2003)[68]	n = 3 Age = 45-74 years PTA = 86-107 dB HL	Word and sentence scores in quiet, sentence scores in noise Speech and noise from frontal loudspeaker	Binaural scores were better than monaural scores on average No individual data reported No significance level reported	Data from adults and children were combined
7. Ching et al (2004)[42]	Nucleus CI-22 (n = 3), CI-24 (n = 18) Total n = 21 Age = 25-84 years PTA = 98-100 dB HL	Sentence scores with speech from hearing aid side and noise from cochlear implant side (60° to the right or left) Sentence scores with speech and noise from frontal loudspeaker	Frontal speech in noise: +7 =14 Spatially separated speech and noise: +8 =5	CI + HA experience was not directly related to speech perception benefit
8. Hamzavi et al (2004)[69]	n = 7 Age = 38-79 years PTA = −125 dB HL	Scores obtained with recorded numbers and monosyllables tests, scores for sentence material presented with live voice	+3 =4	Ceiling effect
9. Iwaki et al (2004)[70]	Nucleus 22 or 24 n = 6 Age = 48-84 years PTA = 92-119 dB HL	SRT for 50% correct Monosyllables and sentences in quiet at 65 dB SPL	Monosyllables and sentences in quiet +3 =3	

		Sentences in noise for 3 configurations: S_0N_0, S_0N_{HA}, S_0N_{CI}	No individual data reported for speech perception in noise	
10. Dunn et al (2005)[53]	Nucleus 24 (n = 6), Clarion (n = 6) Total n = 12 Age = 48-83 years	Word and sentence scores CNC words in quiet CUNY sentences at a fixed SNR for 3 configurations: S_0N_0 (speech and noise from front), S_0N_{HA} (speech from front and noise from hearing aid side), S_0N_{CI} (speech from front and noise from CI side)	Words in quiet: +4, =8 Sentences in noise: +7, =2, −2 Monaural head-shadow (CI) + 8, =3 (HA) +3, = 2 Binaural squelch (CI) +5 (HA) + 6	Unaided hearing thresholds in nonimplanted ear not reported CI volume control adjusted to match loudness of live voice in the hearing aids
11. Kong et al (2005)[71]	Nucleus 24 (n = 2), Clarion (n = 2) Total n = 4	Sentence scores in noise at different SNRs Speech and noise presented from the front	+4	Improvement of CI + HA over CI alone was greater for female than for male masker on target speech produced by a male talker
12. Luntz et al (2005)[72]	Nucleus 24 (n = 2), Clarion (n = 1), MED-EL C40 (n = 2) Total n = 5 PTA = 83-125 dB HL	Sentence test in noise at 10 dB SNR, with speech and noise presented from the front	+1 =3	Ceiling effect
13. Morera et al (2005)[73]	Nucleus 24 n = 12 Age = 23-75 years PTA = 48-115 dB HL	Sentence and word scores In quiet at 55 dB and 70 dB SPL In noise at 10 dB SNR for 3 configurations: S_0N_0, S_0N_{HA}, S_0N_{CI}	Speech in quiet: +3 =9 Speech in noise S_0N_0: +6, =6 S_0N_{HA}: +4, =8 S_0N_{CI}: +6, =6	Devices adjusted to balance loudness between ears People with preimplant word recognition >20% derived greater benefit
14. Mok et al (2006)[74]	Nucleus 24 n = 14 Age = 37-83 years	Word and sentence scores CNC words at 65 dB SPL Sentences at 65 dB with babble at 10 dB SNR SNR for 71% correct spondees in noise, using 3 configurations: S_0N_0, S_0N_{HA}, S_0N_{CI}	CNC words in quiet (n = 14): +3, =11 Sentences in noise (n = 10): +4, =6 Spondees in noise (n = 10) S_0N_0 :+3, =7 S_0N_{HA}: +1, =7, −1 S_0N_{CI}: +4, =6	Unaided thresholds not reported 6 adjusted HA volume controls to match the loudness of tester's voice in their cochlear implants; others reported that HAs were softer than CIs; there was no difference in CI + HA − CI scores for the two groups
Adults: bilateral CI				
15. Van Hoesel et al (1993)[75]	Case report Sequential, Nucleus 22 n = 1	Words and sentences in quiet Sentences in babble noise at 10 dB and 5 dB SNR	=1	Binaural advantage was greater at worse SNR

(continued)

Table 2. (continued)

Study	Subjects	Method/Outcomes Measure	Results	Comments
		from the same loudspeaker positioned at 0° azimuth		
16. Van Hoesel and Clark (1999)[76]	Case report Sequential, Nucleus 22 n = 1	Sentences in noise at 5 dB SNR, with speech and noise from 2 loudspeakers positioned at ±45°	+1	
17. Mueller et al (2000)[77]	Sequential, MED-EL Combi 40/+ n = 3 Age = 35-60 years	Word and sentence scores in quiet and in noise	Sentences in quiet: +2 =1 Sentences in noise (1 tested): +1	Ceiling effect for sentences in quiet
18. Gantz et al (2002)[54]	Simultaneous, Nucleus CI-24M n = 10 Age = 35-75 years	Words and sentences in quiet Sentences in noise at 10 dB SNR with speech from the front and noise from the front (S_0N_0), left −45° (S_0N_{-45}) or right 45° (S_0N_{45})	Speech in quiet: +5 =5 Speech in noise: +8 =2	Preimplant and intraoperative measures via promontory stimulation were not significantly correlated with speech perception assessed at 1 year postimplantation
19. Müller et al (2002)[78]	MED-EL C40/40+, simultaneous (n = 3), sequential (n = 6) Total n = 9	Monosyllabic words in quiet at 65 dB SPL Sentences in noise at 10 dB SNR for 3 configurations: S_0N_0, S_0N_{-90}, S_0N_{90}	Speech in quiet: +8 =1 Speech in noise: +6 =3	Same subject group as Schön et al (2002)
20. Schön et al (2002)[79]	Simultaneous (n = 3), sequential (n = 6), MED-EL C40/40+ Total n = 9 Age = 17-66 years	Sentences in quiet at 70 dB SPL and in noise at 3 SNRs Speech and noise presented from a 4-loudspeaker array spanning 360°; the better ear was always closer to the frontal loudspeaker from which speech was presented	+9	Omnidirectional speech processors were used
21. Stark et al (2002)[80]	Simultaneous (n = 6), sequential (n = 11), MED-EL Combi 40/+ Total n = 17	Word and sentence scores in quiet and in noise from the same frontal loudspeaker	Sentences in quiet: =17 Sentences in noise: +11 =6	Ceiling effect in quiet Tested at 4 years postimplantation
22. Tyler et al (2002)[55]	Simultaneous, Nucleus CI-24M n = 9 Age = 35-71 years	Monosyllabic words and sentences in quiet Sentences in noise at 70 dB SPL for 3 configurations: S_0N_0, S_0N_{-90}, S_0N_{90}	Speech in quiet (n = 9): +6 =3 Speech and noise from the front (S_0N_0): +4 =5 Speech and noise separated	Subjects were tested after they had 3 months' experience with bilateral implants

			Head diffraction: +7 Squelch: +1 S_0N_{-90}: =6 S_0N_{90}: +3 =4	
23. Van Hoesel et al (2002)[33]	Case study Nucleus CI-24 n = 1 Age = 51 years	Sentence scores for speech in babble noise at 5 dB SNR Speech and noise from the front Speech from front, noise from 90° left or right	=1	No difference between the standard rate of 250 pps and a high-stimulation rate strategy of 1800 pps
24. Van Hoesel and Tyler (2003)[56]	Simultaneous n = 4 Age = 36-71 years	SRT for 50% correct BKB sentences at 65 dB SPL in noise 3 configurations: S_0N_0, S_0N_{-90}, S_0N_{90}	Speech and noise from front: =4 Speech and noise separated: Head diffraction: +4 Squelch: +2 =2	
25. Schleich et al (2004)[81]	Sequential, MED-EL Combi 40 or 40+ n = 21 Age = 18-67 years	Sentences in noise: 3 conditions with speech from the front, and noise from the front or ±90°: (S_0N_0, S_0N_{-90}, S_0N_{90}) Compare bilateral with unilateral SRTs for 50% correct	Head diffraction (monaural): +16, =1, −1 Binaural squelch: +4, =10, −5 Binaural summation: +15, =3, −1	Volume settings separately adjusted for unilateral and bilateral conditions SRT not measurable for 3 subjects
26. Senn et al (2005)[31]	Sequential, MED-EL Combi 40+ n = 3 Age = 50-53 years	Sentence scores for speech from the front in quiet and in noise, with noise from 90° to right or left	Quiet: =3 Noise from the side of the first implant: +3 Noise from the side of the second implant: =3	Subjects were tested after they had 1 to 2 years' experience with bilateral implants
Children: bimodal fitting				
27. Chmiel et al (1995)[82]	n = 6 Age = 5-13 years PTA = 106 dB HL	Sentence and word scores in quiet	+3 =3	
28. Simons-McCandless and Shelton (2000)[83]	Nucleus CI-22 (n = 3), CI-24 (n = 1) Total n = 4 Age = 7-16 years PTA = 96-106 dB HL	Word and sentence score	=4	
29. Ching et al (2000)[84]	Nucleus CI-22, CI-24 n = 5 Age 6-18 years	Sentence and consonant scores in babble noise at 10 dB SNR, both from frontal loudspeaker	+5	Significant CI + HA benefit, regardless of whether SPEAK or ACE strategy was used
30. Ching et al (2001)[59]	Nucleus 22 or 24 n = 11 Age = 6-18 years PTA = 88-118 dB HL	Sentences and nonsense syllables in quiet and in babble at 10 dB SNR	Sentences in quiet and in noise: +4 =7	

(continued)

Table 2. (continued)

Study	Subjects	Method/Outcomes Measure	Results	Comments
				Hearing aids were adjusted with cochlear implants by using a systematic procedure to optimize speech intelligibility and balance loudness (see Ching et al, 2004)[83]
6. Luntz et al (2003)[68]	n = 6 Age = 5-15 years PTA = 91-110 dB HL	Word and sentence scores in quiet, sentence scores in noise Speech and noise from frontal loudspeaker	Binaural scores were better than monaural scores on average No individual data reported No significance level reported	Data from adults and children were combined
31. Dettman et al (2004)[85]	n = 9 Age = 7-17 years PTA = 73-122 dB HL	Word and sentence scores in quiet Binaural scores were better than monaural scores on average No individual data for different listening conditions reported		
32. Ching et al (2005)[60]	Experienced CI + HA users (n = 8), New CI + HA users (n = 10) Total n = 18 Age = 6-18 years PTA = 81-115 dB HL	Sentence scores in babble Speech and noise from front Speech from HA side, noise from CI side	Speech and noise from front: +6 =7 Speech and noise separated: +11 =7	Hearing aids adjusted with cochlear implants by using a systematic procedure (Ching et al, 2004)[83]
33. Holt et al (2005)[86]	n = 10 (only 5 completed the 2-year assessment) Nucleus 24, Clarion, MED-EL Combi 40+ PTA = 78-81 dB HL	Scores for PBK words in quiet Scores for words in HINT-C sentences in quiet and in noise at 5 dB SNR, with speech and noise from frontal loudspeaker	Words in quiet at 1 year: +4, =4 Words in quiet at 2 years: +2, =3 Sentences in quiet at 2 years: +4, =1 Sentences in noise at 2 years: +5	Measured at 1 and 2 years' experience with bilateral implants
12. Luntz et al (2005)[72]	Nucleus 24 (n = 6), Clarion (n = 1) Total n = 7 Age = 7-16 years PTA = 90-115 dB HL	Sentence test in noise at 10 dB SNR, with speech and noise presented from the front	Bimodal fitting: ≤6 months bimodal use: +4 >6 months bimodal use: +6 −1	Correlation between unaided thresholds and CI + HA benefit was not significant
34. Litovsky et al (2006)[62]	n = 10 Age = 6-14 years Aided thresholds varied from 30 to 100 dB	SRT for 79.4% correct identification of 25 spondees in babble Target words from front,	Quiet: +1, =3, −6 Front: +5, =1, −4 Near CI: +5, −5 Near HA: +3, =2, −5	Loudness not balanced between ears for some subjects; on average, SRTs were

		babble from front, or from 90° to right or left		similar to those of children with bilateral CIs Large individual variability
Children: bilateral CI				
35. Mueller et al (2000)[77]	Simultaneous (n = 1), sequential (n = 2), MED-EL Combi 40+ Total n = 3 Age = 4-17	Word and sentence scores in quiet and in noise	Speech in quiet and noise: +3	Results at 6 months postimplantation
36. Vermeire et al (2003)[87]	Case report Nucleus CI-24, sequential n = 1 Age = 5 years	Sentence identification (4AFC) and sentence recognition	+1	Hyperbilirubinemia and auditory neuropathy
37. Kühn-Inacker et al (2004)[88]	Simultaneous (n = 1), sequential (n = 17), MED-EL Combi40 or 40+ Total n = 18 Age = 3-9 years	Words in quiet and in noise at +15 dB SNR Speech from 2 loudspeakers 90° apart and noise from 2 loudspeakers 90° apart	+17, =1	Subjects had 6 to 24 months' experience with bilateral implants at the time of testing Age at implantation and time lag between 2 implants did not affect performance
38. Litovsky et al (2004)[63]	Sequential, Nucleus CI-22 + CI-24 (n = 1), CI-24 + CI-24 (n = 2) Total n = 3 Age = 8-12 years	SRT for 79.4% correct identification of 25 spondees in babble Target words from front, babble from front, or from 90° to right or left	Quiet: +1, −1 Noise from front: +1, −2 Noise from first CI: +2, =1 Noise from second CI: =3	Results at 2 to 3 months after second CI, 3 to 8 years between first and second CI Matched loudness perception in two ears
26. Senn et al (2005)[31]	Sequential, MED EL Combi 40+ n = 2 Age = 14 years	Sentence scores for speech from the front in quiet and in noise, with noise from 90° to right or left	Quiet: =2 Noise from first CI: +2 Noise from second CI: +1, =1	Results at 2 years after second CI 1 to 2 years between first and second CI
34. Litovsky et al (2006)[62]	Nucleus CI-22 or CI-24 (n = 9), Clarion (n = 1) Total n = 10 Age = 3-14 years	SRT for 79.4% correct identification of 25 spondees in babble Target words from front, babble from front, or from 90° to right or left	Quiet: +7, =1, −2 Front: +6, =1, −3 Near first CI: +6, =2, −2 Near second CI: +6, =1, −3	On average, children with bilateral CIs and children with CI + HA had similar SRTs

Note: In the "Subjects" column, "simultaneous" refers to users who received bilateral implants during the same operation, whereas "sequential" refers to users who received two implants in two operations with a time lag between the first and the second device. Pure tone average (PTA) at 0.5, 1, and 2 kHz is shown where reported. In the "Method/Outcomes Measure" column, "S_0N_0" represents tests in which speech and noise were presented from the front, "S_0N_{HA}" represents tests in which speech was presented from the front and noise from the side with a hearing aid, "S_0N_{CI}" represents tests in which speech was presented from the front and noise from the side with a cochlear implant, "S_0N_{-90}" represents tests in which speech was presented from the front and noise was presented from the left side, and "S_0N_{90}" represents tests in which speech was presented from the front and noise was presented from the right side. In the "Results" column, the number of subjects who obtained significant binaural benefits is indicated by "+," who performed similarly across monaural and binaural conditions is indicated by "=," and who performed poorer binaurally than monaurally is indicated by "−."

improved localization with binaural hearing is possible for some people (see Table 1), even if they could rely only on interaural level differences. Across studies, rms errors with cochlear implant alone ranged from 40° to 60°, which might be reduced to around 20° to 30° when binaural hearing was available either by using bimodal hearing devices or by bilateral implantation. As shown in Table 1, there is a wide range of performance across subjects in different studies, varying from high accuracy, side-dominated, limited, to no localization ability.[52] Many individuals did not obtain binaural advantages (as indicated by the number of individuals designated as "=" in studies summarized in Table 1), no matter whether binaural hearing was provided with CI + HA or with CI + CI (CI, cochlear implant; HA, hearing aid).

Differences in methodologies and subject characteristics across studies contributed to mixed findings. Although 3 of the studies reported results from groups of subjects using either CI + CI or CI + HA assessed with the same measures,[52,61,63] the findings were inconclusive. These studies do not provide unbiased estimates of treatment effects because differences in results are confounded by the lack of baseline equivalence between groups of subjects who used bimodal hearing devices and those who used bilateral implants.

The occurrence of side-dominated errors in localization both for users of bimodal stimulation and users of bilateral implantation supports the need for developing better fitting strategies to enhance binaural hearing. Further research into mechanisms underlying variations in performance across individuals is necessary to better understand which stimulation mode and fitting strategy can best enhance individual performance on binaural tasks.

Speech Perception

To examine the binaural benefits arising from bilateral stimulation, typically monaural (with CI alone) scores in percentage or speech reception thresholds (SRTs) in terms of SNR are compared with binaural scores or SNRs. Binaural benefit is defined as higher speech scores or speech thresholds obtained at less favorable SNR in the binaural condition (with CI + HA or CI + CI) than in the monaural condition (with CI alone). Table 2 shows the studies on speech perception, separately for adults and for children. In the table, we report the numbers of subjects who derived significant benefits, no benefits, and degraded performance when comparing binaural with monaural hearing in each study.

Head diffraction, squelch, redundancy, and complementarity. The combined effect of head diffraction, binaural squelch, redundancy, and complementarity may be quantified by presenting speech and noise from spatially separated sources and comparing the binaural score to the monaural score of the ear nearer to the noise source. Availability of input from both ears makes selective attention possible, and the ability to attend to the ear with a better SNR is demonstrated by users of bimodal hearing devices as well as users of bilateral implants. Across all studies, the binaural improvement in terms of SNR, or the effect size, is about 2 dB for children using either bimodal hearing devices or bilateral implants and ranges from 1 to 3 dB for adult users of bimodal hearing devices and up to 6 dB for adults with bilateral implantation (see Table 3).

Squelch, redundancy, and complementarity. The combined effect of binaural squelch, redundancy, and complementarity may be quantified by presenting speech and noise from spatially separated sources and comparing the binaural score to the monaural score of the ear further away from the noise source. Unless binaural processing is used to achieve noise suppression, the binaural score would be expected to be worse than the monaural score when adding the ear with a poorer SNR. Across all studies on bimodal hearing and bilateral implantation, many individuals demonstrated binaural benefits for speech perception in some test condition. As shown in Table 3, the effect size because of squelch, redundancy, and complementarity is of the same order of magnitude as that arising from the combined effect of redundancy and complementarity. The contribution of squelch is open to question, in light of the evidence showing that users of bimodal hearing devices were not able to make use of interaural time difference cues for speech perception in noise[90,91] and that users of bilateral implants had very limited ability to make use of interaural time difference information.[32,92]

Binaural redundancy and complementarity. The combined effect of binaural redundancy and complementarity can be assessed by presenting speech with or without competing noise from the front at 0° azimuth and comparing subjects' performance when they listened with 1 ear to performance when they listened

Table 3. Size of Binaural Advantages in Speech Perception

	Binaural-Monaural		
	Head Diffraction + Squelch + Redundancy + Complementarity	Squelch + Redundancy + Complementarity	Redundancy + Complementarity
Bimodal			
Children	1.5-2 dB[32]		1-1.5 dB[12,29,30,31,32]
Adults	1-2 dB[5,7,10]	1 dB[10,13]	1-2 dB[1,2,3,4,5,7,8,9,10,11,12,13,14]
	3 dB[13]		3 dB[9]
Bilateral			
Children	2 dB[26]	1-2 dB[26,37]	1 dB[26,35]
Adults	1 dB[16]	1 dB[19,22,25,26]	1-2 dB[17,18,19,21,22,25]
	3-4 dB[18,19,22,23,26]	2 dB[20,24]	
	6 dB[24]		

Note: The superscript numbers refer to the studies in Table 2.

with two ears. The effect is more evident when listening to speech in noise than in quiet often because of ceiling effect in the latter[77,80] (see Table 2). Across all studies on bimodal hearing and bilateral implantation, the effect size, in terms of SNR, is about 1 to 2 dB (see Table 3). No detrimental effect with binaural hearing was reported for either users of bimodal hearing devices or users of bilateral implants.

Complementarity. The effect of complementarity arising from the use of a hearing aid with a cochlear implant results in better discrimination of speech in noise because of voice segregation and better perception of voicing and manner cues in consonant identification.[59,71,93] Kong et al[71] demonstrated that when subjects used CI + HA, they perceived speech better when target male speech was presented in a female masker than in a male masker, whereas when they used CI alone, a female or a male masker was equally effective in masking the target male speech. Apparently, the addition of a hearing aid provided low-frequency information that assisted with perception of speech in the presence of a competing talker by facilitating segregation of voices on the basis of fundamental frequency cues.

In studies that examined consonant confusions, information transmission analyses revealed that more voicing and manner information were transmitted when subjects wore a hearing aid with a cochlear implant, compared with the use of a cochlear implant alone.[59,93] As shown in Table 4, this applies to adults and children alike. In a similar vein, Turner et al[94] showed that acoustic hearing in the low frequencies complemented high-frequency cues when both modes of stimulation were combined in the same ear.

Summary and discussion. Across all studies, about half of the subjects showed binaural benefits in some test conditions, and most of the remaining demonstrated similar performance between monaural (with CI alone) and binaural (with CI + HA or CI + CI) conditions. Table 3 demonstrates that the binaural improvements in terms of effect sizes associated with bimodal hearing and bilateral implantation are similar in magnitude. The improvements in speech perception are mainly attributed to head diffraction and binaural redundancy. In addition, users of bimodal hearing devices benefit from the effect of complementarity. A few subjects were reported to have performed better with monaural than binaural hearing provided by either bimodal hearing devices[53] or bilateral cochlear implants.[81] The mixed findings and the range of binaural benefits among subjects reported in the literature highlight the need to investigate factors affecting successful use of binaural hearing with either modes of bilateral stimulation. As with localization, the evidence on the relative efficacy of bimodal hearing and bilateral implantation for speech perception is inconclusive because of methodological limitations in published studies.

Sound Quality and Music Perception

It is known that users of cochlear implants have difficulty identifying voices of speakers[95] and recognizing environmental sounds and musical instruments.[48,96] Users of cochlear implants tend to rate the quality of

Table 4. Relative Information Transmitted in Consonant Perception With a Unilateral Cochlear Implant (CI) and With a Cochlear Implant and a Hearing Aid (CI + HA).

		Mean (SD)			
	Condition	% Total Information	% Voice	% Place	% Manner
Adult (N = 16)	CI	71 (12)	53 (21)	45 (17)	55 (22)
	CI + HA	75 (11)	64 (25)	50 (18)	66 (17)
Child (N = 11)	CI	54 (14)	37 (14)	28 (30)	45 (22)
	CI + HA	62 (15)	49 (23)	34 (28)	59 (19)

Note: Mean and standard deviation (SD) are shown.

Table 5. Summary of Reasons for Using Hearing Aids With Cochlear Implants, Compared With Using Cochlear Implants Alone, by Adult Users

Study	Reasons for Using a Hearing Aid With a Cochlear Implant
Armstrong et al (1997)[66]	More natural sound
	Sound is heard in both ears
	Own voice quality is improved
	A "full communication potential" is available
Blamey et al (1997)[97]	Hear sounds in both ears
	"Naturalness" of overall percept
Tyler et al (2002)[51]	Gives "clarified" hearing
	Feels more comfortable hearing sounds in both ears
	Hearing aid "adds to a little more hearing level while cochlear implant gives the word and voice clarity"
Syms and Wickesberg (2003)[67]	Better sound quality
Ching et al (2004)[42]	Adds more "brilliance" to people's voices
	Music is more enjoyable
	Gives a 'better balance'
	Easier to identify talker in a group
Hamzavi et al (2004)[69]	More speech-like sound quality

musical sounds poorly, and their recognition of melodies, especially when rhythmic cues are not available, is near chance level (for a comprehensive review, see McDermott[50]). These have been attributed to the deficient spectral and pitch information conveyed by cochlear implants. For people who received a unilateral cochlear implant and who have usable acoustic hearing, perception of sound quality and music can be enhanced by combining acoustic with electric hearing in contralateral ears.

Kong et al[71] examined the recognition of 12 familiar melodies by 5 adult users of CI + HA. The melodies were generated in low-frequency, midfrequency, and high-frequency ranges, and rhythmic information was eliminated by equalizing the duration of each note and the silent intervals between notes. Melody recognition with hearing aid alone (HA), CI alone, and CI + HA were measured for each frequency condition. Whereas performance with CI alone was at chance level, performance was 17 percentage points better with HA alone and with CI + HA. This pattern of results was observed for 4 of the 5 subjects. Recognition of melody by implant users was undoubtedly enhanced by using a hearing aid in the opposite ear.

Furthermore, users of bimodal hearing devices reported an improvement in voice and sound quality as well as music perception when they used a hearing aid with a cochlear implant than when they used a cochlear implant alone (see Table 5). They commented that it was easier to recognize people's voices, they enjoyed music more, and the quality of sounds in the environment was more natural and clear when they used bimodal hearing devices than when they used a cochlear implant alone.

These studies support the potential enhancement of sound quality and music perception by combining acoustic and electric hearing in two ears. Recent reports on combining acoustic and electric hearing in the same ear also demonstrate similar benefits.[98,99]

Overall Summary

The evidence to date establishes that the use of bimodal hearing devices brings improvement over the use of a cochlear implant alone. In a similar vein, the use of bilateral cochlear implants enhances performance over the use of a unilateral cochlear implant. Results across all studies attest to localization and speech perception advantages that can be attributed to a combination of head diffraction and redundancy for some listeners. In addition, bimodal hearing offers advantages in speech perception and music perception because of complementarity. The low-frequency residual acoustic hearing complements the high-frequency electric hearing, which is especially beneficial for segregating voice sources, for perceiving voicing information in consonants, and for perception of sound quality and music. These benefits are consistent with research on people who combined acoustic with electric hearing in the same ear.[100-103]

No conclusions can be drawn on whether bimodal hearing devices or bilateral implants offers greater advantages for people who received a cochlear implant and who have residual hearing in the contralateral ear because of 3 major reasons. First, data cannot be directly compared across studies on people with bimodal fitting and bilateral implants because baseline equivalence between groups was not established and methods of assessments were not uniform. Even in the studies that used the same assessments for the bilaterally implanted group and the bimodal hearing group, no attempts were made to match the groups. The use of nonblinded assessments might have confounded the results, as positive effects of bilateral implantation might have been exaggerated because of the considerable cost involved in implantation. As there were no randomized controlled trials or crossover trials, methodological limitations in the published studies preclude meaningful comparisons of data. Second, the potential binaural advantages for bimodal hearing users with residual hearing might have been underestimated in current literature. The published studies mostly reported performance of subjects with PTAs of 90 dB HL or much greater (see Ching[89] for a summary), whereas many implant recipients now have better residual hearing in the nonimplanted ear because of progressive relaxation in cochlear implant candidature. It is likely that the relative efficacy of bimodal hearing would improve with better residual hearing in the nonimplanted ear[52] and with advances in digital hearing aid technology. Last but not least, most of the earlier studies did not attempt to adjust hearing aids and cochlear implants to complement each other or to balance loudness between ears. This might have impacted negatively on binaural performance as better binaural hearing might be achieved with systematic fine-tuning of hearing aids with cochlear implants.[59]

In principle, it is plausible that the binaural system would have greater ability to compare the two ears when the inputs match (as in bilateral implants) than when the inputs differ (as in combining a hearing aid with a cochlear implant). On the other hand, complementary information from separate frequency bands (CI + HA) might yield greater benefit than combining information from overlapping bands (CI + CI). This hypothesis is supported by experiments on segregation of voices between target and competing talkers[71] and information transmission analyses of consonant confusions of users of CI + HA (see Table 4). It is also consistent with research indicating that frequency bands that are separated provide "new" information that contributed more to speech intelligibility than bands that are adjacent.[104-106]

To better understand whether a hearing aid is more or less beneficial than adding a second implant to a recipient of unilateral cochlear implants who has residual hearing in the nonimplanted ear, we commenced a crossover trial in which the same persons experienced both stimulation methods. In the next section, we report the pilot results from two subjects.

A Crossover Trial in Two Cochlear Implant Users

The purpose of this pilot study was to document speech perception, localization, and functional performance in two adults who used a cochlear implant and a hearing aid in opposite ears and who subsequently received a second cochlear implant. Biographical data for the two subjects are shown in Table 6. Audiometric thresholds in the unaided ear are shown in Figure 1.

Subject S1 had 26 years of experience using bilateral hearing aids prior to implantation but ceased using a hearing aid in the nonimplanted ear after receiving a cochlear implant in the left ear for about 4 years. Subsequently, he started wearing a hearing aid in the nonimplanted ear. At the time of

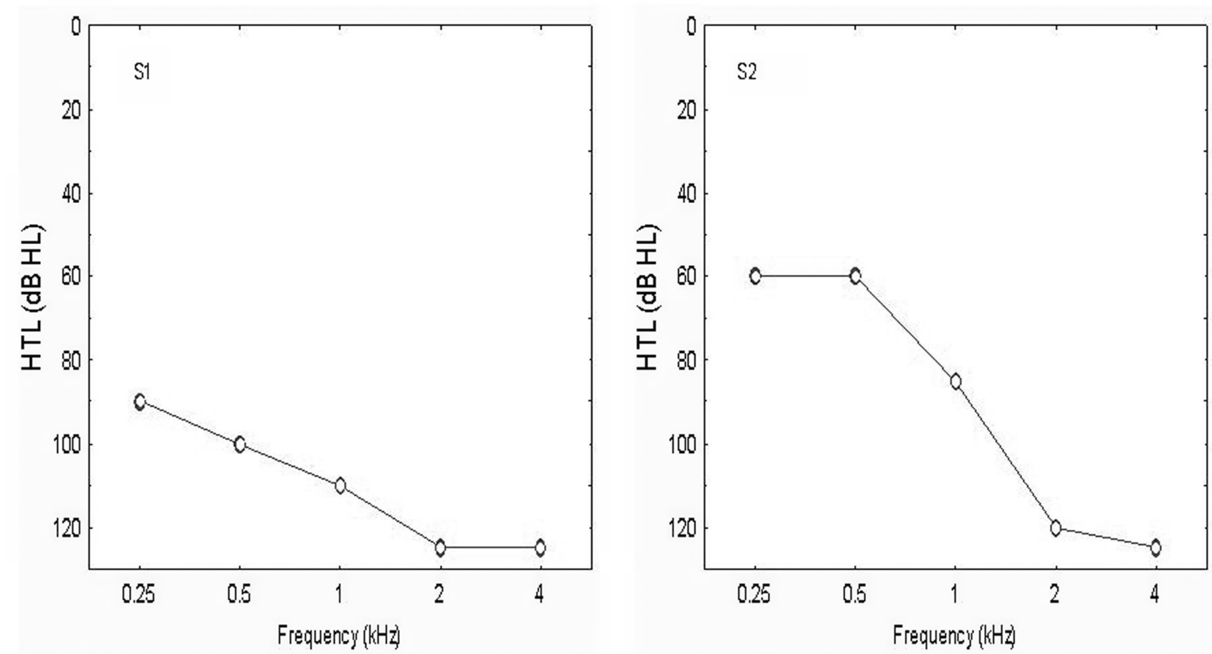

Figure 1. Hearing threshold levels of the nonimplanted ear of subjects S1 and S2.

Table 6. Biographical Data for Subjects S1 and S2

	Age (Years)	Etiology	Type of Hearing Aid	Type of Cochlear Implant	Length of Cochlear Implant Use (Years)	Length of Bimodal Use (Years)	Duration of Deafness (Years)
S1	47	Genetic	Bernafon AF120	Nucleus 24	4.7	0.5	11
S2	67	Unknown	Bernafon AF120	Nucleus 24	4.3	4	20

participation, he had been wearing his hearing aid with his cochlear implant for about 6 months. Subject S2 had used bilateral hearing aids for 15 years prior to implantation and had continued to use a hearing aid in the contralateral ear after receiving a cochlear implant in the left ear. At the time of participation, he had been using a hearing aid with a cochlear implant for 4 years. The hearing aids of both subjects had been adjusted with their cochlear implants by using a systematic procedure[107] prior to participation in the study.

Both subjects subsequently chose to receive a second cochlear implant when this option was available. The time lag between the first and second implant was 5 years 6 months for both subjects.

Test Methods

To compare performance using CI, CI + HA, and CI + CI, localization ability, speech perception, and functional performance in real life were measured.

Localization. Localization was assessed by using a horizontal array of 11 loudspeakers spaced 18° apart, located in an anechoic chamber. All loudspeakers were closely matched using software-controlled digital filters. The subject was seated directly facing the center of the array, at a distance of 1 m. Each test stimulus was a 0.83-second train of 4 pulses of pink noise, with 150-millisecond pulse duration, 10-millisecond rise/fall times, and a 50-millisecond interpulse interval. The nominal presentation level of the stimulus was 70 dB sound pressure level (SPL), with actual levels varying randomly around the nominal level by ±3 dB. The subjects were instructed to look at a loudspeaker positioned at 0° while awaiting a noise presentation but were free to look around after the noise began. They were asked to decide where noise bursts originated. Six runs, each with randomized presentations of 11 stimuli, were conducted for each condition. Performance was scored as the error between the source loudspeaker and the response loudspeaker indicated by the subject. Root mean square error in terms of degrees was calculated for each condition.

Speech perception. Two experiments were conducted. The first experiment aimed to compare binaural functioning with bimodal hearing devices to that with bilateral implants and to examine if binaural functioning develops over time. Tests were conducted under the following listening conditions: cochlear implant alone, a hearing aid and a cochlear implant together, and two cochlear implants together. Performance with unilateral implants was compared to that with bimodal hearing devices and to that with bilateral implants. Measurements with bilateral implants were carried out at several time intervals after the activation of the second implant. Speech perception was measured in the sound field, with speech presented from a loudspeaker positioned at 0° azimuth at 65 dB SPL and uncorrelated noise simultaneously from two loudspeakers positioned at ±90°. Two measurements were made as follows: SNR for 50% correct recognition of sentences and percentage correct identification of consonants embedded in nonsense syllables. In the first measurement, the City University of New York (CUNY) sentence material[108] was used. Sentences were presented at 65 dB SPL, and the noise level was adjusted adaptively in 1-dB steps to determine the SNR for 50% correct recognition of keywords in the sentences. In the second measurement, nonsense syllables in the form of vowel-consonant-vowel (VCV) were used. The vowel (V) /a/ was used, and the consonant (C) was one of /p b t d k g f v Θ ð s z ʃ ʒ tʃ dʒ m nŋ l r j w h /. Four lists each of 24 consonants were administered for each listening condition at 5 dB SNR.

The second experiment aimed to compare binaural intelligibility level differences obtained with bilateral implants and with bimodal hearing devices. The speech material was the Bamford-Kowal-Bench Australian (BKB-A) sentences,[109] which were presented in uncorrelated noise in both ears. Speech and noise were mixed and presented via direct audio input to the hearing aid and the implant speech processor simultaneously. The level of the speech and noise stimuli was separately adjusted for each ear to achieve the same level across ears. To determine the SNR for 50% correct identification of keywords in the sentences, the level of the noise was adjusted in 1-dB steps adaptively. In the S_0N_0 condition, there was no interaural time difference in the noise between ears. In the S_0N_{700} condition, an interaural delay of 700 microseconds was introduced in the noise presented to the ears. The delayed noise was presented first in the left ear. Then, testing was repeated with the delayed noise presented in the right ear. Where there was a difference in SNR found between ears for the delayed condition, the better SNR of the two was taken. Binaural intelligibility level difference (BILD) was expressed as the difference in SNR between the S_0N_0 condition and the S_0N_{700} condition.

Functional performance in everyday life. Two questionnaires were used to determine the relative effectiveness of bimodal hearing devices and bilateral implants in everyday life: the Speech, Spatial, and Qualities of Hearing Questionnaire (SSQ, Gatehouse and Noble[110]) and the National Acoustic Laboratory Functional Performance Questionnaire (NAL-FQ). The SSQ yields 3 subscale scores: speech, spatial, and quality of hearing, and a total overall score. The NAL-FQ yields 3 subscale scores: listening in quiet situations, listening in noisy situations, awareness of environmental sounds, and a total overall score. The two questionnaires were provided to the subjects one week prior to a test session. The completed SSQ was returned to the experimenter, and the NAL-FQ was administered at a face-to-face interview by the experimenter during the test session. Scoring of the NAL-FQ was carried out by the experimenter, on the basis of the real-life examples provided by the subject in answer to each item.

All measures were completed within one test session, with the speech perception tests preceding the localization tests, followed by the functional questionnaires.

Results and Discussion

Localization. Figures 2 and 3 show the results from the localization tests. Subject S1 performed at chance for the unilateral implant (CI alone) condition and the implant and hearing aid condition (CI + HA) and demonstrated improvement with bilateral implants at 6 weeks and further at 7 months after implantation. Standard errors of the means were calculated for the localization rms errors from each run presented for each test condition. A difference score was considered significant at the 5% level when it exceeded two standard errors of the mean. There was a significant reduction of localization rms error ($P < .05$) from 55° for the CI + HA condition to 24° for the bilateral implant (CI + CI) condition at 7 months after subject S1 received the second

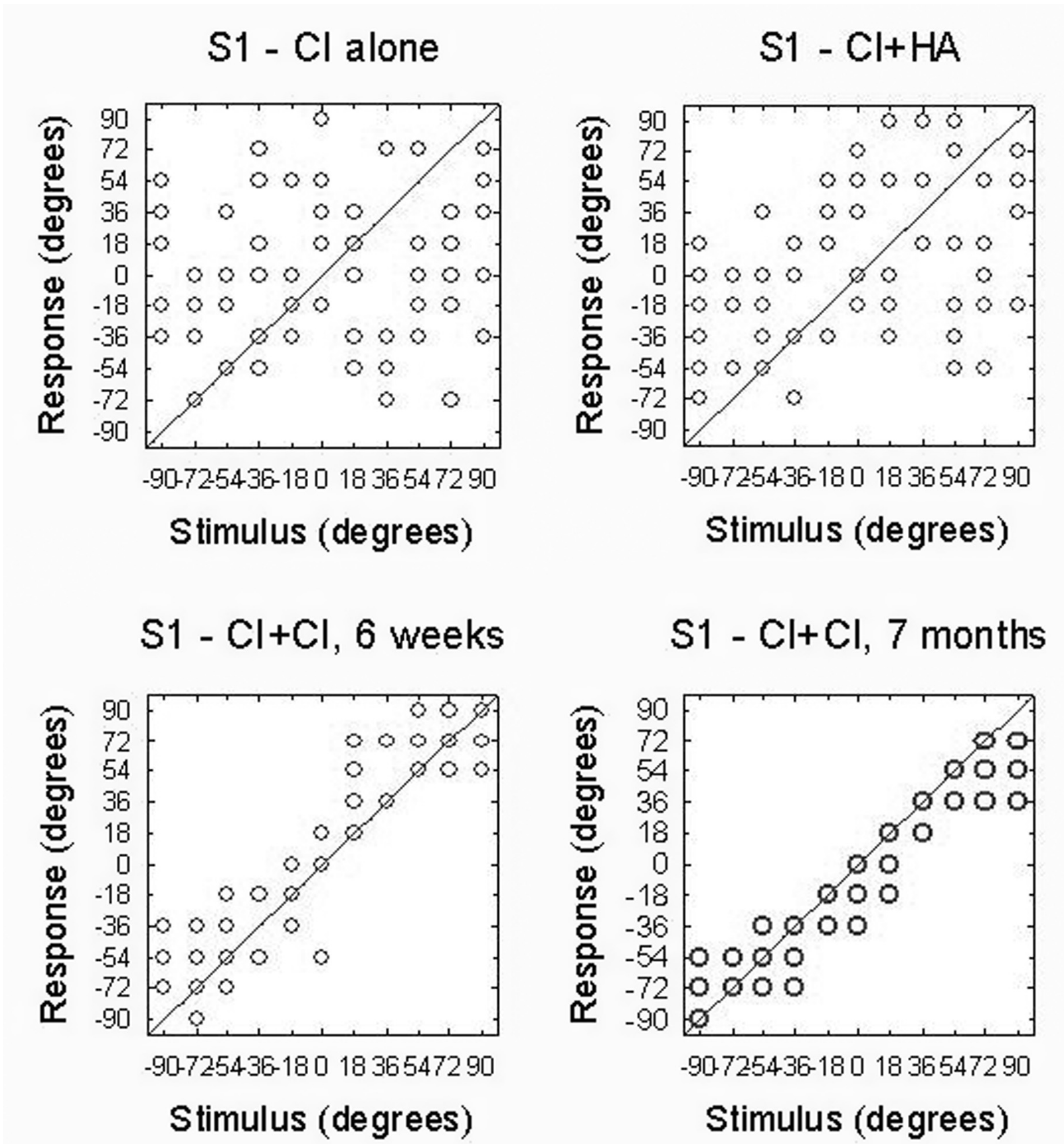

Figure 2. Localization performance of subject S1 with the first implant alone (CI alone), with the first implant and a hearing aid (CI + HA), and with bilateral implants (CI + CI) at two intervals after activation of the second implant.

implant. Subject S2 performed at chance for the CI alone and the CI + HA conditions. There was a significant reduction of rms error from 54° for the CI + HA condition to 38° for the CI + CI condition at 3 months after implantation ($P < .05$). However, performance with bilateral implants at 6 months postimplantation showed degraded performance for no known reason.

Speech perception. Performance for speech perception in the sound field is shown in Figure 4. The left panel shows the SRTs at 50% correct in terms of SNRs. The right panel shows the scores for consonant perception in percentage correct.

Standard errors of the difference between scores for CI + HA and CI + CI conditions were calculated using scores from each list for each test condition. A

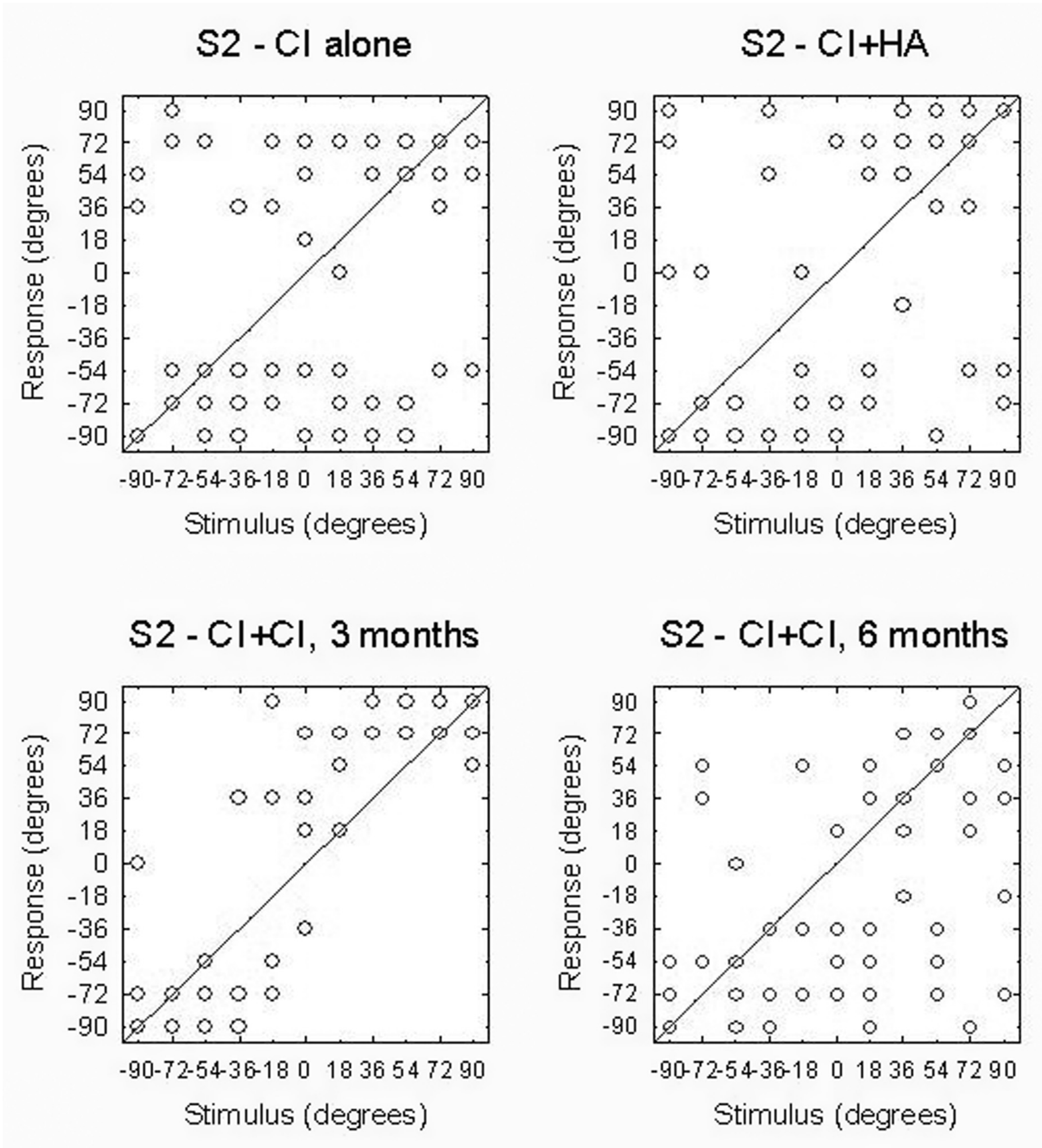

Figure 3. Localization performance of subject S2 with the first implant alone (CI alone), with the first implant and a hearing aid (CI + HA), and with bilateral implants (CI + CI) at two intervals after activation of the second implant.

difference score was considered significant at the 5% level when it exceeded two standard errors of the mean. For subject S1, sentence recognition was significantly poorer at 12 months than at 6 months after activation of the second implant. He was not available for testing for other conditions. His consonant perception at 6 months after receiving the second implant was comparable to that with bimodal hearing devices and that with a unilateral cochlear implant. His performance was degraded at 12 months postimplantation. Subject S2 improved in sentence recognition by 2 dB SNR from CI alone to CI + HA and a further 5.4 dB from CI + HA to CI + CI at 6 months after activation of the second

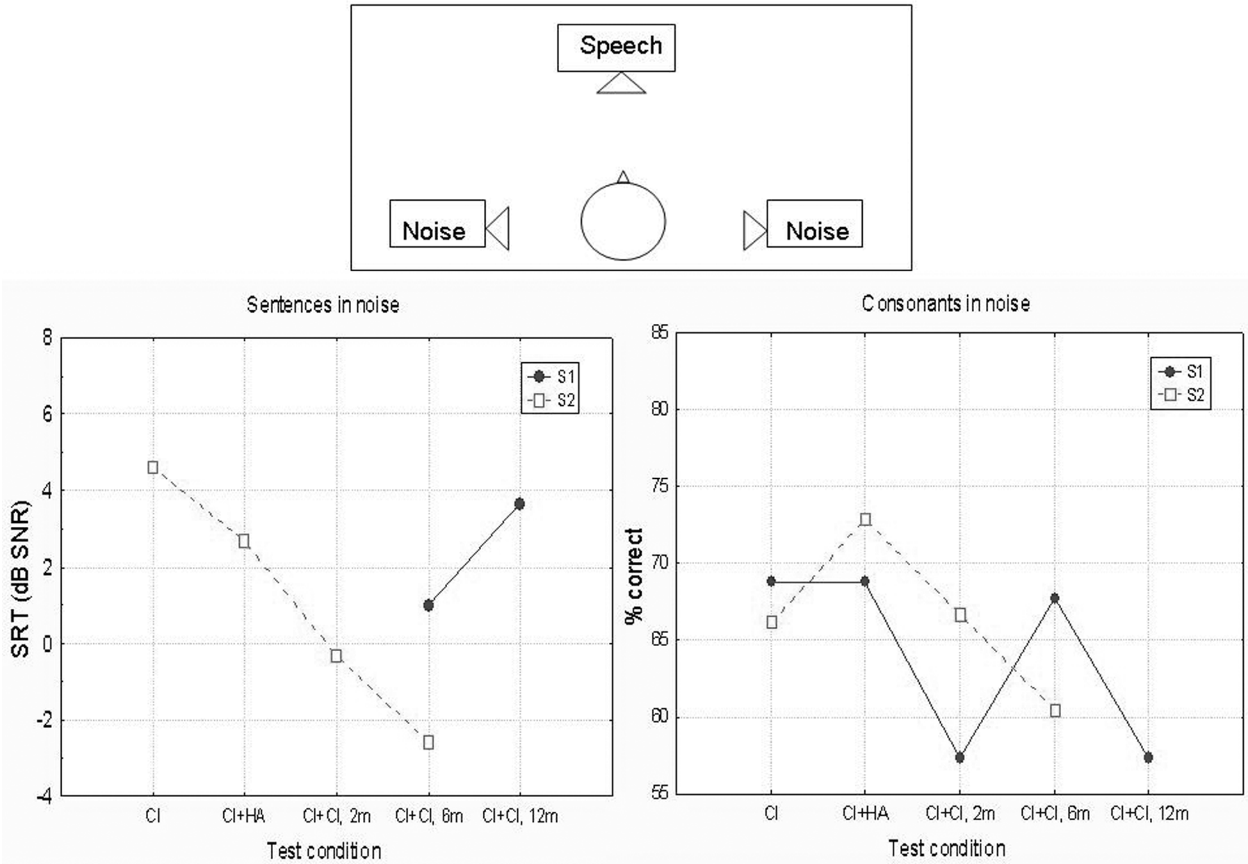

Figure 4. Binaural speech perception with speech from the front and noise from left and right simultaneously. The left panel shows the speech reception threshold (SRT) in terms of dB signal-to-noise ratio (SNR). The right panel shows the percentage of correct scores for consonants. Filled circles represent results from subject S1, and open squares represent results from subject S2.

implant. However, consonant recognition was significantly reduced from 73% correct with CI + HA to 61% correct with CI + CI at the 6-month interval. Consonant confusion matrices were examined by using an information transmission analysis.[38] A feature system that consisted of 3 major categories was used to characterize the 24 consonants: voicing (voiced / b d g m n ŋ v ð z ʒ dʒ l r j w / vs voiceless / p t k f Θ s ʃ h tʃ /); place (bilabial /p b m w / vs labiodental or dental /f v Θ ð / vs alveolar / t d n s z l / vs postalveolar / r / vs palatal / j ʃ ʒ tʃ dʒ / vs velar/glottal / k g ŋ h /); and manner (plosive / p b t d k g / vs fricative / f v Θ ð s z ʃ ʒ h / vs affricate / tʃ dʒ / vs nasal / m n ŋ / vs glides/liquids / j w l r /). Table 7 gives, for each subject, the relative information transfer for voicing, place, and manner with CI alone, CI + HA, and CI + CI at 6 months after activation of the second implant. Both subjects received more voicing information when using CI + HA than when they were using CI alone or CI + CI, demonstrating the benefit because of complementarity when a hearing aid was used with a cochlear implant.

Figure 5 shows the BILD for the two subjects. There was no difference in performance no matter whether the noise delay was introduced in the left ear or the right ear, indicating that neither subject was able to make use of interaural time differences for sentence perception in noise when using CI + CI at 6 months after activation of the second implant. Subject S1 did not show binaural release of masking with CI + HA either. At 12 months after activation of the second implant, subject S2 did not demonstrate binaural release of masking on the basis of interaural time difference information.

Functional performance questionnaires. Figure 6 shows the questionnaire scores for subject S1. There was no measurable functional advantage in changing

Table 7. Relative Information Transmitted in Consonant Perception by Subjects S1 and S2 When They Used a Cochlear Implant Alone (CI), a Cochlear Implant and a Hearing Aid (CI + HA), and Bilateral Implants (CI + CI) After 6 Months' Experience

Subject	Listening Mode	% Total Information	% Voice	% Place	% Manner
S1	CI	76.8	66.1	50.4	72.9
	CI + HA	86.3	75.5	70.5	78.3
	CI + CI	84.1	57.1	70.9	83.9
S2	CI	80.7	69.0	61.8	82.1
	CI + HA	84.7	81.0	62.2	91.7
	CI + CI	77.8	49.5	52.4	79.9

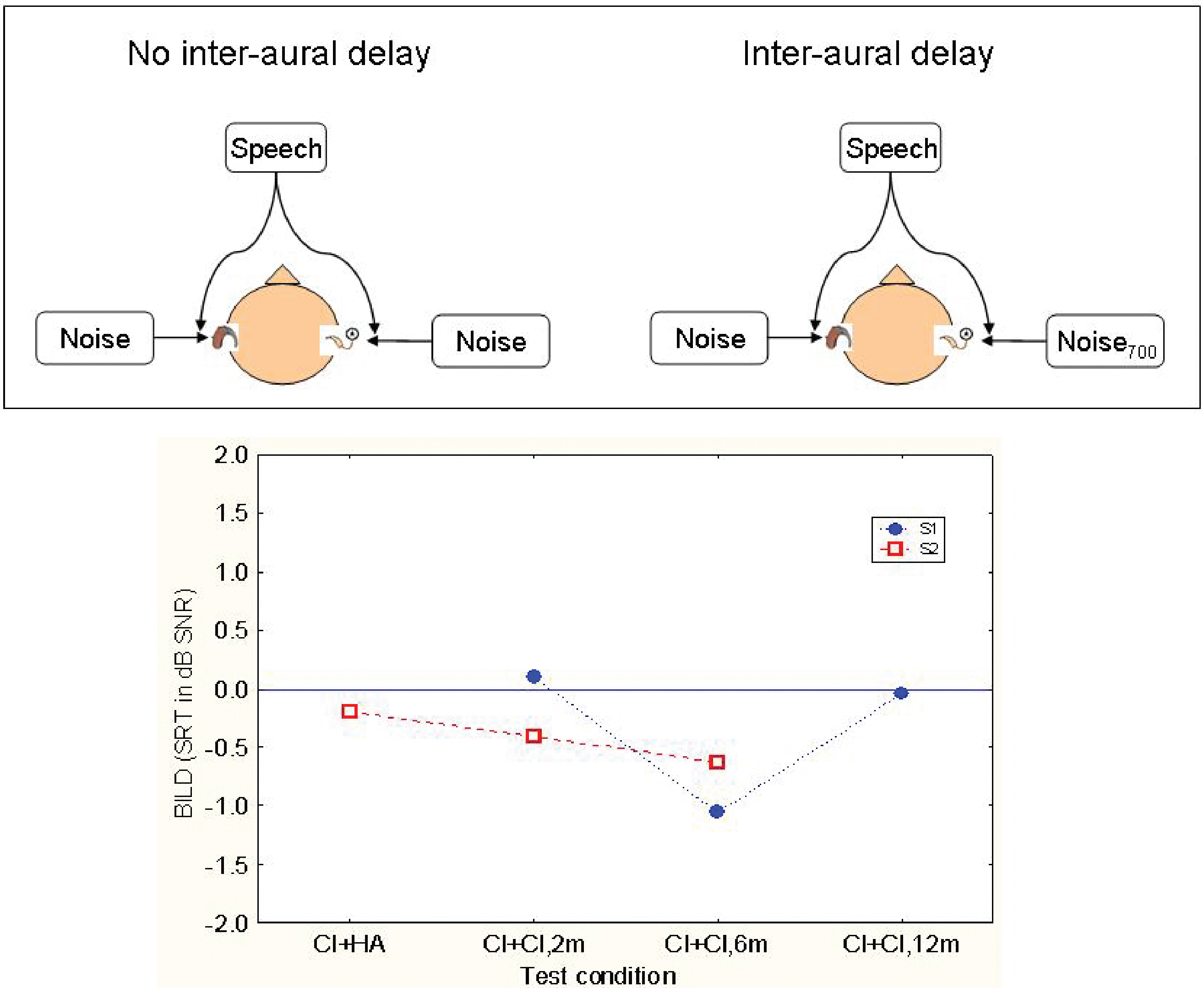

Figure 5. Binaural intelligibility level difference (BILD) expressed as the difference in speech reception threshold (SRT) between the condition with no interaural delay and the condition when an interaural delay of 700 microseconds was introduced in the noise in dB signal-to-noise ratio (SNR). Filled circles represent the results for subject S1, and open squares represent results from subject S2.

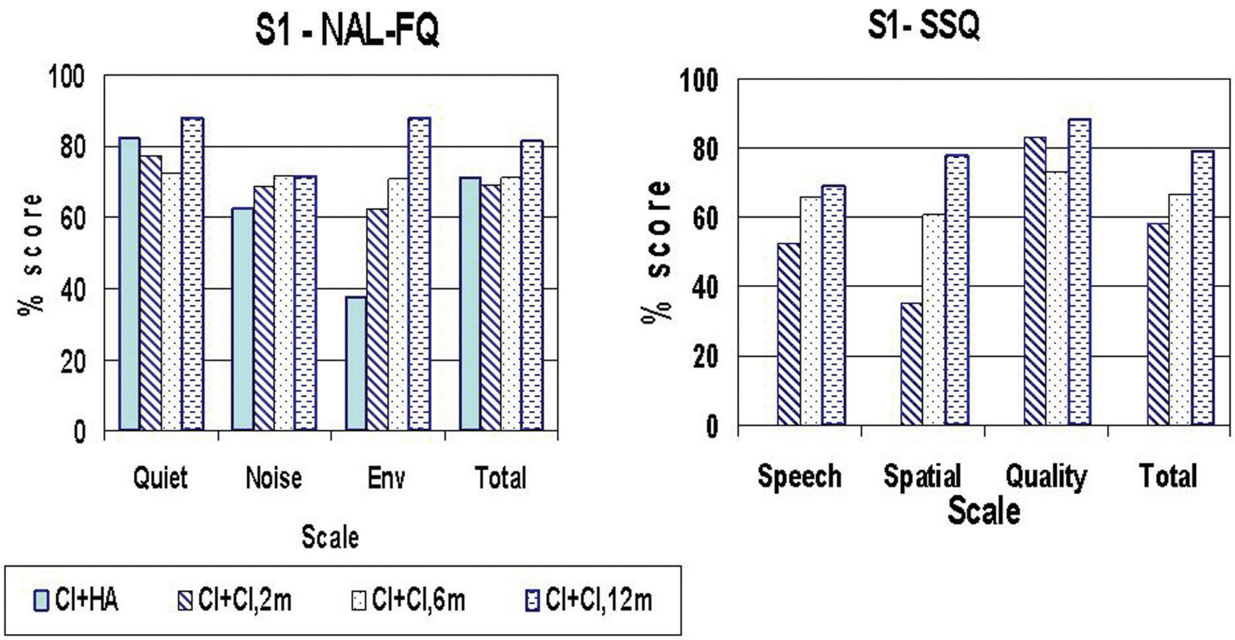

Figure 6. Functional performance of subject S1 when using his first implant with a hearing aid (CI + HA) and his two cochlear implants at two months (CI + CI, 2m), 6 months (CI + CI, 6m), and 12 months (CI + CI, 12m) after activation of the second implant. The left panel shows results of the National Acoustics Laboratory Functional Performance Questionnaire (NAL-FQ). The subscale scores of listening in "Quiet," listening in "Noise," awareness of environmental sounds ("Env"), and the "Total" overall scores are shown. The right panel shows results from the Speech, Spatial, and Quality of Hearing Questionnaire (SSQ), with the subscale scores for "Speech," "Spatial," and "Quality" and the "Total" overall scores. SSQ scores are available for only the bilateral implant conditions.

from bimodal hearing devices to bilateral implants when measured using the NAL-FQ at the 6-month interval. When measured at 12 months after bilateral implantation, subject S1 showed a significant improvement in environmental awareness in the results from the NAL-FQ (based on test-retest critical differences obtained in Ching et al[42]) and an improvement in the spatial hearing subscale score of the SSQ. Figure 7 shows the scores for subject S2. His NAL-FQ scores were not significantly different across test conditions. His SSQ scores revealed that CI + CI improved his spatial hearing compared with CI + HA. The scores for the speech and quality subscales were similar for both conditions.

Summary and discussion. This preliminary investigation explored whether bimodal hearing devices or bilateral implants were more beneficial for two adult users of cochlear implants. Following are the main observations:

- Bilateral CI improved localization significantly for subject S1 but not for subject S2.
- Sentence perception in noise was better with CI + HA than with CI alone for subject S2. His performance continued to improve with CI + CI over 6 months after implantation.
- Consonant perception with CI alone and CI + HA was similar for subject S1. His CI + CI scores were similar or poorer than CI + HA.
- Consonant perception with CI + HA was better than CI alone for subject S2. His CI + CI scores were poorer than CI + HA.
- Neither subject demonstrated the ability to use interaural time difference cues for sentence perception in noise with CI + CI.
- Functional performance in environmental awareness and spatial hearing improved with bilateral implantation. For subject S1, functional performance increased over 12 months after bilateral implantation.

The magnitude of improvement in localization ability demonstrated by subject S1 at 6 weeks and then at 7 months after activation of the second implant clearly indicated superior localization with CI + CI than with CI + HA. However, his CI + CI consonant scores were either similar or lower than the CI + HA scores (see Figure 5). In contrast, S2 did not derive localization benefits at 6 months after activation of the second implant, but he obtained

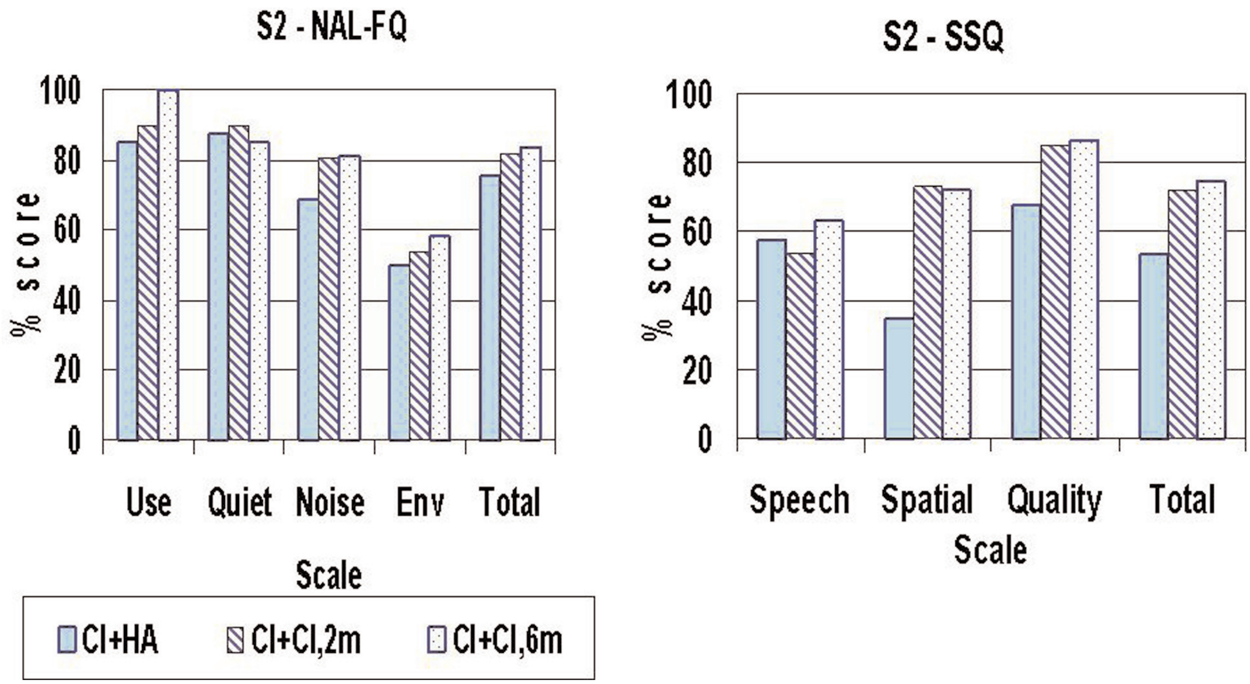

Figure 7. Functional performance of subject S2 when using his first implant with a hearing aid (CI + HA) and using his two implants at two months (CI + CI, 2m) and 6 months (CI + CI, 6m) after activation of the second implant. The left panel shows subscale and total scores based on the National Acoustic Laboratory Functional Performance Questionnaire (NAL-FQ), and the right panel shows subscale and total scores for the Speech, Spatial, and Quality of Hearing Questionnaire (SSQ).

significant benefits in sentence perception in noise at the same time interval. His consonant scores for CI + CI were degraded compared with CI + HA.

The pilot results from these two subjects suggest that binaural functioning with two implants develops over time, even for adults who had prior experience with bimodal hearing devices. Subject S1 took only two months after activation of the second implant to derive localization benefits, whereas subject S2 did not obtain similar benefits even at 6 months after implantation. On the other hand, subject S2 continued to improve in sentence perception in noise over 6 months after the second implant was activated, and his performance with CI + CI surpassed that with CI + HA. Subject S1 did not show any speech perception improvement even at 12 months after the activation of the second implant. In fact, the SRT for sentence perception was worse at 12 months than at 6 months of bilateral implant experience. The factors that affect an individual's potential for binaural benefits are not known, and the time course for development of binaural functioning to asymptote remains to be investigated.

Further research with a larger sample of people with better residual hearing in the nonimplanted ear using controlled crossover designs will be necessary to determine whether better binaural hearing is likely to be achieved through bimodal hearing devices or bilateral implantation. It will also be of interest to identify factors influencing individual performance with two devices in performing different binaural tasks. Some factors affecting effective use of bimodal hearing devices for children have been reported,[111] but more research on factors influencing the success of bimodal fittings and bilateral implantations needs to be carried out to develop guidelines for effective habilitation.

Who Should Have Binaural/ Bimodal Fittings?

Whereas there is clear evidence to support the provision of binaural hearing as the standard of care for bilaterally hearing-impaired listeners, there is currently insufficient evidence to guide decisions about whether bimodal fitting or bilateral implantation would provide greater benefit for an individual who already uses a unilateral cochlear implant. As the studies summarized in Tables 1 and 2 are descriptive studies designed to examine whether the intervention can work under optimal conditions with involved professionals and highly motivated subjects who have relatively uncomplicated conditions, higher-level evidence is needed to evaluate the relative effectiveness of bimodal hearing devices and bilateral implants.

An international consensus on bilateral cochlear implants and bimodal stimulation[112] identified several advantages of bilateral cochlear implantation, including: (1) the better ear is always implanted, given that it is difficult to predict which ear will give the best speech understanding postoperatively; (2) allows bilateral cortical stimulation; and (3) restores binaural hearing. The first goal requires further consideration, especially in light of the disadvantages relating to procedure costs and to the fact that implantation makes future techniques difficult or impossible to use. Cost-effective analyses do not support the provision of a second implant to postlingually deafened adults who already use an implant unilaterally.[113] The results from a randomized controlled study of 24 adults further indicated that receiving a second implant had a small and inconsistent effect on quality of life.[114] The study also highlighted some problems associated with the second implant, including negative changes in tinnitus (4 out of 8 subjects who had no tinnitus preimplantation reported tinnitus postoperatively) and mismatch in insertion depths, making it difficult to tune the two implants to give a fused percept of binaural stimuli. When recipients of unilateral cochlear implants have usable residual hearing in the nonimplanted ear, the second and third goals can be equally well achieved with hearing aid fitting.

Although a reason for implanting two ears may include the assurance that the better ear is always implanted, it must surely not be the primary reason if alternative methods of habilitation are possible (as when there is usable residual hearing, even if only in the low frequencies) and are likely to be equally beneficial. A reasonable criterion for bilateral implantation ought to require that significantly more benefits can be obtained from bilateral implantation than from other forms of intervention.

It must also be remembered that performance with bilateral implant systems is limited by the nerve survival and function in the individual, and some people may not have sufficient residual auditory capacity in the central nervous system to make use of binaural cues.[115] Our review of the literature has revealed that benefits of bilateral cochlear implants were obtained by only some individuals and only in some test conditions. The performance with bilateral implants also relies on the technology of the systems and the fitting schemes used. Currently, bilateral implants rely on the use of independent processors, and implants are individually adjusted. As such, the time difference between signals arriving at the two ears may be distorted or misrepresented by the temporally uncoordinated presentations of stimulation pulses to the two ears. Independent gain controls would also distort interaural level differences. Future developments in binaural signal processing that better preserve fine temporal information to enhance perception of pitch and of interaural time difference cues would lead to greater benefits. The use of a linked automatic gain control for both devices may also better preserve fidelity of interaural level differences to enhance binaural cues. The same limitations and goals would be expected to apply when bimodal hearing devices are used, although achieving synchronized timing within the two cochleae would be more difficult.

Current evidence has established the efficacy of cochlear implants over hearing aids for children with profound hearing loss. On average, implanted children achieved similar levels of language and speech development as an average hearing-aid user with hearing loss around 80 dB HL.[116,117] A cross-sectional survey in the United Kingdom revealed that implanted children whose preimplantation hearing levels were greater than 118 dB HL achieved auditory performance and academic abilities that were equivalent to those of nonimplanted children with unaided hearing levels of 80 to 104 dB HL.[118] Functional performance of children whose preimplantation hearing levels were greater than 110 dB HL and who used bimodal hearing devices achieved levels that were equivalent to bilaterally aided children who have moderate to severe hearing loss.[119]

Given the potential advances in technology, gene therapy, hair-cell regeneration, stem cells, and other possible future treatments for hearing loss,[120,121] one must question bilateral implantation in children who have significant residual hearing. The relative efficacy of bimodal hearing devices and bilateral implantation may change from that reported in previous studies, as earlier diagnosis of hearing loss and intervention with advanced hearing aid technology are now possible with implementation of newborn hearing screening programs, and these are likely to lead to better performance with amplification. Fitting a hearing aid to the nonimplanted ear with residual hearing that is usable with acoustic amplification will help to avoid auditory deprivation. Additional research is necessary to determine the guidelines for choosing between bimodal fitting and bilateral implantation.

Notwithstanding the accumulating research studies in support of the provision of binaural hearing devices, there may be some people who have deficits in binaural processing such that better performance is obtained with a unilateral device than with bilateral devices (this phenomenon has been observed for bilateral hearing aid wearers; see for example, Arkebauer et al[122] and Jerger et al[123]). Potential causes hypothesized include asymmetrical distortion in the two cochleae and distorted or delayed interhemispheric transmission via the corpus callosum. If the latter is true, then it is also likely to be a problem for some people who receive bilateral implants. For purely auditory reasons, not every person who satisfies the audiological criteria for implantation will be a successful user of bilateral implants or bimodal hearing devices.

The evidence to date supports the recommendation of providing binaural/bimodal fittings as the standard of care for recipients of unilateral cochlear implants who have residual hearing in the nonimplanted ear.[112]

How Should Binaural/Bimodal Fittings Be Prescribed?

A major goal of binaural/bimodal fitting is to ensure that both the hearing aid and the cochlear implant provide audible and comfortable outputs corresponding to a wide range of input levels. For people who use only hearing aids, or only cochlear implants, there are validated procedures to achieve this goal.[124,125] For bimodal fitting, because the dynamic range of acoustic and electric hearing differs, application of conventional hearing-aid fitting procedures and cochlear implant mapping procedures often resulted in loudness mismatch between ears.[126] The difference in loudness between ears has been reported in several studies, and in some cases, the users of CI + HA adjusted the volume controls in either hearing aids or cochlear implants to achieve some loudness matching between ears.[51,53,73,74] Tyler et al[51] reported that two users of CI + HA who adjusted volume controls of the two devices until sounds merged demonstrated a binaural advantage for localization, and one showed a significant binaural advantage for speech perception in noise. A third subject reported that the sound from the implant lagged behind that from the hearing aid in time and that he found this somewhat irritating. Despite this, his CI + HA speech scores were significantly higher than his CI alone scores, and his localization ability was improved from chance level in the monaural condition to 85% correct in the binaural condition. Mok et al[74] indicated that 6 users of CI + HA adjusted their hearing aid volume controls to match the loudness of a live voice in their cochlear implants, and 8 users reported that the voice was softer in their hearing aids than in the cochlear implants. On average, the former group did not obtain more binaural benefits in speech perception than the latter.

There is some evidence to suggest that systematic fine-tuning of a hearing aid to complement a cochlear implant and balancing the loudness between ears enable better binaural hearing to be achieved with the use of bimodal hearing devices in speech perception and localization.[42,59] The bimodal fitting procedure involved prescribing and verifying hearing aid characteristics based on the NAL hearing aid prescription,[127,128] fine-tuning according to individual preferences based on intelligibility judgments, and finally balancing the loudness of the hearing aid with the cochlear implant in a systematic way (see Ching et al[107] for a step-by-step guide). Table 8 shows the preferred frequency response slope and required gain after individual systematic fine-tuning and the frequency response and gain prescribed by the NAL prescription. Results from 22 adults and 48 children indicated that the NAL prescription provides appropriate frequency response slope and overall gain, both for children and adults, on average.

The procedure outlined above was based on adjusting the hearing aid after the setting of the cochlear implant is stabilized, whereas an ideal bimodal fitting scheme would allow comfortable levels to be established and balanced between acoustic and electric inputs in a single procedure with simultaneous adjustment of the implant and hearing aid for both ears. A systematic fine-tuning procedure should then be implemented for each individual to ensure that most information of the speech signal is presented in the most effective part of the hearing

Table 8. Hearing Aid Frequency Response and Gain Requirements of Children and Adults

		Frequency Response		Gain	
		Prescribed (NAL-RP)	Preferred	Prescribed (NAL-RP)	Required
Adult (N = 22)	Mean	1.1 dB/oct	1 dB/oct	51	47.5
	SD	3.8	4.1	8.5	9.7
	Range	−5.5 to 8	−5 to 9.5	36 to 63	27 to 61
Child (N = 48)	Mean	−0.2 dB/oct	−2.1 dB/oct	55	53
	SD	3.2	3.1	7.1	7.9
	Range	−7.5 to 6.5	−7.5 to 6.5	36 to 69	36 to 71

range in each ear. As residual acoustic hearing is often best in the low frequencies, maximizing audibility in the low frequencies via acoustic hearing enables the user to extract salient pitch cues that complement the midfrequency and high-frequency information provided by electric hearing. Amplifying the high frequencies where hearing loss is severe can be detrimental to speech perception.[74,129,130]

There were early attempts on using a single speech processor to provide inputs to a hearing aid and a cochlear implant simultaneously,[65] but this method was not superior to the use of a conventional hearing aid with a cochlear implant. This is not surprising as the devices received their inputs from a single microphone, thereby removing cues to localization and binaural squelch. More recently, the adaptive dynamic range optimization (ADRO, Blamey[131,132]) processor has been designed to be fitted in the same way to cochlear implants and hearing aids. The processor allows for continual adaptations of the wide range of input levels to the restricted dynamic range of the listener. In principle, the use of a single binaural processor to preserve the fidelity of interaural level differences by a single automatic gain control is likely to provide benefits in addition to those provided by two independent devices. The effectiveness of this mode of bimodal fitting relative to other methods remains to be investigated.

Conclusions

Although there are many unresolved issues concerning the relative efficacy of CI + HA and CI + CI for recipients of unilateral cochlear implants who have significant residual hearing in the nonimplanted ear, it is unequivocal that stimulation should be provided to that ear to achieve binaural hearing. The evidence demonstrates that binaural benefits for localization and speech perception can be obtained by many individuals using either bimodal stimulation or bilateral implantation. This is because of the combined effects of head diffraction, redundancy, squelch, and complementarity. The effect of complementarity is greater in the bimodal mode (CI + HA) than in the bilateral implant mode (CI + CI) because low-frequency information provided by acoustic hearing complements high-frequency information provided by electric hearing. This is supported by evidence on voice segregation, consonant perception, and music perception. There is currently insufficient evidence to guide decisions on which option for bilateral stimulation is better for which individual. Further research is necessary to improve current technology and fitting strategies to support binaural hearing and to gain better understanding of factors affecting performance with binaural hearing devices.

Acknowledgments

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